

Higgs Decays to Unstable Neutrinos: Collider Constraints from Inclusive Like-Sign Dilepton Searches

Linda M. Carpenter¹ and Daniel Whiteson¹

¹*Department of Physics and Astronomy
University of California, Irvine, CA 92697*

We study the pair production of fourth generation neutrinos from the decay of an on-shell Higgs produced by gluon fusion. In a fourth generation scenario, the Higgs branching fraction into fourth generation neutrinos may be quite large. In the case that the unstable heavy neutrinos are a mixed Majorana and Dirac state, neutrinos pair-produced from Higgs decay will yield a substantial number of like-sign dilepton events. In this article we use inclusive like-sign dilepton searches from hadron colliders to constrain the theoretical parameter space of fourth generation leptons.

PACS numbers:

I. INTRODUCTION

A fourth generation is among the simplest possibilities for new physics at the weak scale. If a fourth generation exists, recent work has shown that bounds on unstable fourth generation leptons may be well under 100 GeV, making the leptons the lightest new states. Heavy unstable fourth generation neutrinos would decay through the process $N_1 \rightarrow \ell W$. Fourth generation neutrinos may be light, LEP placed mass bounds under 100 GeV [1] [2]. Most generally, fourth generation lepton sectors may have neutrinos with mixed Dirac and Majorana masses and, in this case, mass bounds on the lightest neutrinos may be 62.1, 79.9 or 81.8 GeV, depending on whether the final state lepton is τ , μ , or e [3].

If a fourth generation exists, Higgs physics may provide a powerful handle for constraining these models. The dominant Higgs production mode at both Tevatron and LHC is gluon fusion, $gg \rightarrow h$. This process proceeds through a heavy-quark loop and is substantially enhanced by the presence of fourth generation quarks. The enhancement is largely independent of quark mass and gives an increase in Higgs production of approximately a factor of eight compared to production in the Standard Model, see for example [4] [5].

The presence of fourth generation particles also greatly effects the Higgs branching fractions. For SM Higgs masses up to 160 GeV, the Higgs decay width is dominated by decay to bottom quarks; however, this proceeds through a Yukawa coupling that is not extremely large. If other heavier states exist in the theory, they may easily dominate and require us to look for the Higgs in non-standard channels. For example, many recent 'hidden Higgs' scenarios yield highly altered Higgs branching fractions and a variety of standard Higgs final states, for example see [6]-[10]. A fourth-generation lepton sector also offers new channels for Higgs decays. Fourth generation neutrinos with both Dirac and Majorana masses will have significant couplings to the Higgs depending on the Dirac mass component. In fact, as long as the Dirac mass parameter is larger than the bottom mass, the Higgs decay width to neutrinos will dominate that of bottoms for any sufficiently heavy Higgs mass. In the window of Higgs masses between roughly 120 and 160 GeV, the dominant branching fraction of the Higgs may be to heavy neutrinos. For larger values of the Higgs mass, where the decay channel into on-shell electro-weak gauge bosons is open, the branching fraction into neutrinos is still significant, remaining above 10 percent for Higgs masses up to 200 GeV and above one percent up to 500 GeV.

In principle fourth generation neutrinos may be stable or unstable, leading to very different Higgs decay signatures. Stable Majorana neutrinos may be quite light, under 50 GeV [11] [12] [13] [14], and the possibility of light stable neutrinos as a Higgs decay channel has been recently explored [15] [16]. Unstable Majorana neutrinos may decay into a standard model charged lepton and a W boson, $N_1 \rightarrow W\ell$. If this decay is flavor-democratic, or is dominated by τ decays, the heavy neutrino may be as light as 61.2 GeV. Since a Majorana neutrino may decay into a SM lepton

of either sign, any process which pair-produces these fourth generation neutrinos produces many like-sign dileptons [17] [18]. As like-sign dileptons are a clear, low-background signature at hadron colliders, the possibility of Higgs decays in this channel is quite interesting. Previous works have proposed searches for heavy neutrino pairs produced from a Z and which decay into like-sign dileptons. In this case, the signal of like-sign dileptons plus jets become an interesting new channel in which to look for the Higgs. If the Higgs production as well as the branching fraction to fourth generation neutrinos are large enough, a simple inclusive like-sign dileptons search may be used to constrain large parts of fourth generation parameter space - this possibility is the focus of this paper. We will use published inclusive same-sign dilepton analyses from LHC and the Tevatron to place constraints on various fourth generation lepton scenarios.

This paper is organized as follows: Section 2 reviews fourth generation neutrino masses and couplings, Section 3 discusses Higgs production and branching fractions in fourth generations scenarios, Section 4 analyses inclusive like-sign dilepton searches at hadron colliders, and Section 5 concludes.

II. REVIEW OF FOURTH GENERATION NEUTRINO MASSES

In the most general case, fourth generation neutrinos may have both a Dirac and a Majorana mass. Note that here we use the notation of [19], where the Lagrangian is

$$L = m_D \bar{L}_4 N_R + M_N N^2 + \frac{m_D}{v} H \bar{L}_i N_R$$

The mass matrix is given by,

$$\mathcal{L}_m = -\frac{1}{2} \overline{(Q_R^c N_R^c)} \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c. \quad (1)$$

where $\psi^c = -i\gamma^2 \psi^*$. There are then two Majorana neutrinos with different mass eigenvalues:

$$M_1 = -(M/2) + \sqrt{m_D^2 + M^2/4}$$

$$M_2 = (M/2) + \sqrt{m_D^2 + M^2/4}$$

The mass eigenstates can be expressed in terms of the left-right eigenstates

$$N_1 = \cos \theta Q_L^c + \sin \theta N_R + \cos \theta Q_L + \sin \theta N_R^c$$

$$N_2 = -i \sin \theta Q_L^c + i \cos \theta N_R + i \sin \theta Q_L - i \cos \theta N_R^c$$

where we have defined the mixing angle

$$\tan \theta = m_1/m_D$$

The Higgs couples to the neutrino mass eigenstates with coupling proportional to powers of the neutrino mixing angle. The Higgs coupling to the lightest neutrino pair is given by

$$\frac{m_D}{v_h} H N_1 N_1 \sin(2\theta).$$

The neutrino mixing angle varies between $\pi/4$ for pure Dirac-type neutrinos and $\pi/2$ for Majorana-type. We see that in the limit where the neutrinos are pure Majorana, m_D approaches zero, the mixing angle θ approaches $\pi/2$, and the Higgs decouples from the neutrinos as required, while for pure Dirac states the coupling is maximal.

III. HIGGS PRODUCTION AND BRANCHING FRACTIONS

At hadron colliders, the largest Higgs production rate comes from gluon fusion. The Higgs-gluon coupling is generated by loops of the heavy quarks. The $gg \rightarrow h$ production cross section is given by

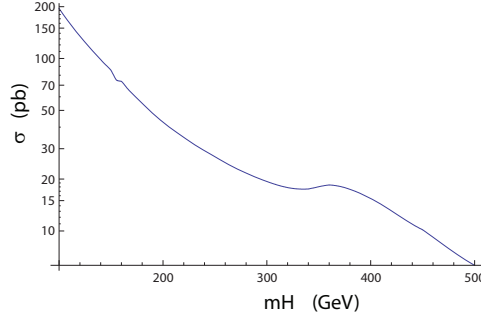


FIG. 1: Dependence of $gg \rightarrow h$ production on Higgs mass, including effects of fourth generation quarks, at LHC with $\sqrt{s} = 7$ TeV.

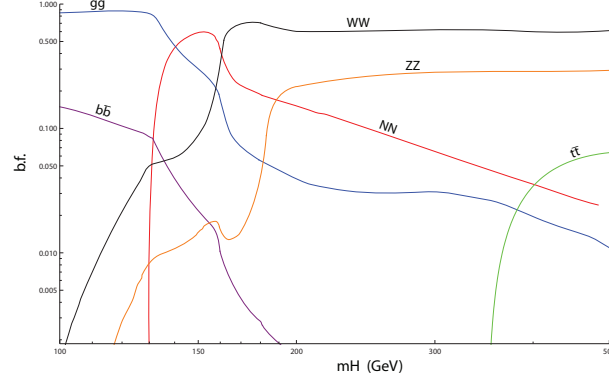


FIG. 2: Dependence of Higgs branching fractions on mass for the benchmark point $m_{n_1} = 63\text{GeV}$, $m_{n_2} = 300\text{GeV}$.

$$\sigma(pp \rightarrow h) = \frac{1}{16} \Gamma(h \rightarrow gg) \frac{16\pi^2}{sm_h} \int_{m_h^2/s}^1 \frac{dx}{x} g(x) g\left(\frac{m_h^2}{sx}\right),$$

where $\Gamma(h \rightarrow gg)$ is the Higgs to gluon decay width

$$\Gamma(h \rightarrow gg) = \frac{\alpha_s G_F m_h^3}{16\sqrt{2}\pi^3} \sum_i (\tau_i (1 + (1 - \tau_i) f(\tau_i)))$$

with

$$\tau_i = \frac{4m_i^2}{m_h^2}, f(\tau_i) = (\sin^{-1} \sqrt{1/\tau_i})^2$$

where the index i runs over heavy quark flavors. Due to their large Yukawa couplings, the additional of fourth generation quarks enhances the $h \rightarrow gg$ decay width substantially; the resulting decay width is largely independent of the new heavy quark mass, and larger than the Standard Model prediction by about a factor of 8. The $gg \rightarrow h$ production cross-section in a fourth generation scenario for LHC is shown in Figure 1; note that the Higgs production remains above a picobarn for Higgs masses up to 500 GeV.

For Higgs masses below twice the W or Z masses, the most important standard model Higgs branching fractions are b quarks and gluons. This changes significantly with the addition of a fourth generation. The Higgs decay width into a Dirac particle is given by

$$\Gamma_D = \frac{m_h y_D^2}{8\pi} \left(1 - \frac{4m_d^2}{m_h^2}\right)^{3/2}$$

The branching ratio is proportional to the square of the Yukawa coupling. We see that the bottom, which normally dominates the Higgs decay for low masses, does not have a particularly large Yukawa coupling. A fourth generation neutrino with substantial Dirac component may easily overtake the bottom decay mode, see Figure 2.

The ratio of $h \rightarrow N_1 N_1$ to $h \rightarrow b\bar{b}$ is

$$\frac{\Gamma(h \rightarrow n_1 n_1)}{\Gamma(h \rightarrow b\bar{b})} = \frac{m_{n_1}^2 \sin(2\theta)}{m_b^2} \frac{(1 - \frac{4m_{n_1}^2}{mh^2})^{3/2}}{(1 - \frac{4m_b^2}{mh^2})^{3/2}}$$

Notice, however, that the coupling is proportional to the mixing angle. Only when the neutrino is in the deep Majorana limit where $\theta \rightarrow \pi/2$ does the Higgs branching fraction to neutrinos drop substantially. Figure 3 shows the effect of mixing angle on Higgs branching fraction. These are contour plots over the N_1, N_2 mass plane for two benchmark Higgs mass values. The branching fraction drops as one increases N_2 mass and enters the Majorana region.

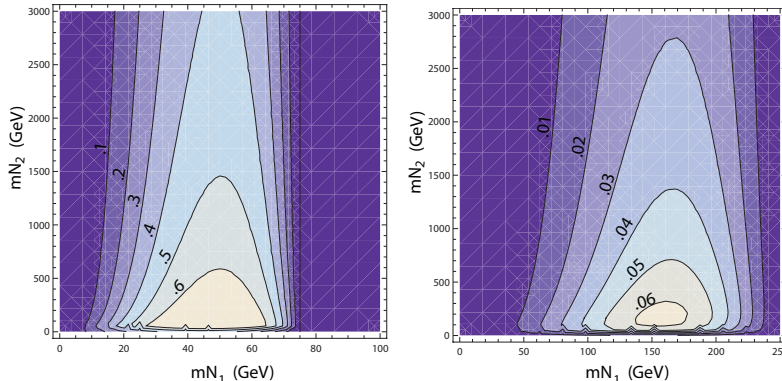


FIG. 3: Higgs branching fraction $h \rightarrow N_1 N_1$ Higgs mass values of 150 GeV (left) and 400 GeV (right).

In the Standard Model, the next largest branching fraction comes from Higgs decaying to gluons. The decay width of Higgs to gluons is given above. With the addition of a fourth generation, the branching fraction of Higgs to gluons is substantially larger than it is in the Standard Model and overtakes that of $h \rightarrow b\bar{b}$ for low masses. However, in the region just above twice the mass of the lightest fourth generation neutrino, $h \rightarrow N_1 N_1$ is the *dominant* decay mode, see Figure 2. Once the Higgs becomes large enough to decay into a pair of on-shell electroweak gauge bosons, this mode dominates the Higgs branching fraction. However, the decay width into fourth generation neutrinos remains larger than all other channels. The Higgs branching fraction to neutrinos remains appreciable, above 10 percent, even for Higgs masses out to 200 GeV and above a percent up to Higgs masses of 500 GeV.

In the heavy Higgs region the most sensitive search channel is the $h \rightarrow ZZ$ mode. However, to suppress the multi-jet background at least one leptonic decaying Z is required, which significantly reduces the cross-section due to the small $Z \rightarrow \ell\ell$ branching ratio. If the Higgs decay to fourth-generation neutrinos is very distinctive, it may remain an important channel for high mass Higgs searches.

IV. COLLIDER BOUNDS

A. LHC

We consider Higgs production from gluon fusion and decay to a pair of light fourth generation neutrinos, where the lightest neutrino is unstable and decays via the process $N_1 \rightarrow W\ell$, giving

$$gg \rightarrow h \rightarrow N_1 N_1 \rightarrow WW\ell\ell \rightarrow \ell\ell + qq' + qq'$$

The $N_1 \rightarrow W\ell$ decay rate is determined by the values of a four-generation lepton mixing matrix. In the simple case that we consider here, we allow only a single decay rate to be non-zero, so that the fourth generation neutrino decays entirely to a single flavor of lepton.

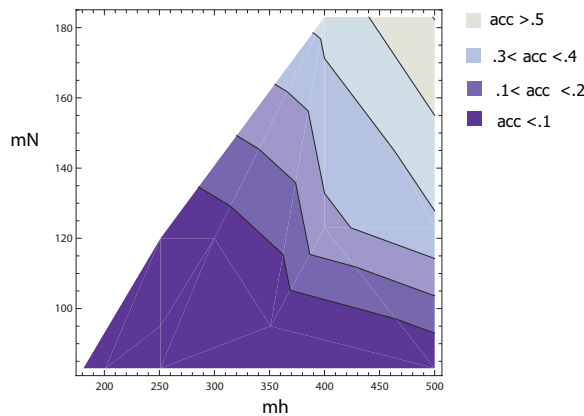


FIG. 4: Plot of ATLAS fiducial region acceptance (defined in text) in the m_h , N_1 mass-plane.

Because the N_1 state is Majorana, it may decay to a final state lepton of either sign with equal probability: thus the decay results in like-sign dileptons half of the time. Therefore, there is a significant rate of Higgs production with decay into states with high p_T like-sign dileptons, a low-background signature.

ATLAS has completed an inclusive like-sign dilepton search which looks for like sign muons of high invariant mass in 34 pb^{-1} of data [20]. Even with a small data set, ATLAS has set limits on the cross-section of like-sign dimuon events at $< 170 \text{ pb}$ in a simple fiducial region. We calculate the predicted cross-section in the ATLAS fiducial region for fourth-generation Higgs decays to to constrain fourth generation parameter space with the inclusive like sign dilepton data. Higgs events were generated using MADGRAPH [21] decayed with BRIDGE [22] and showered with PYTHIA [23]. The fiducial region requires two like-sign muons with

- $p_T > 20 \text{ GeV}$ and $\eta_\mu < 2.5$
- isolation cone of $R > 0.4$ between muons and quarks or gluons
- di-muon invariant mass of $> 110 \text{ GeV}$

The acceptance for $h \rightarrow n_1 n_1 \rightarrow \ell \ell W W$ in this fiducial region is shown in Figure 4. Notice that the acceptance becomes large when the Higgs mass is large, due to the high invariant mass cut on the like-sign leptons. The acceptance also falls as the N_1 mass becomes lighter and the final state lepton becomes soft.

Figure 5 shows the expected exclusion at 95 percent confidence level in the Higgs, N_1 mass plane from ATLAS data for the fixed value $m_{N_2} = 300 \text{ GeV}$. Figure 5 gives an exclusion in the N_1, N_2 mass plane shown for different values of the Higgs mass. For large mixing between neutrinos, light neutrino masses between 100 and 200 GeV can be excluded. Notice that regions of parameter space are ruled out as long as the Higgs branching fraction to neutrinos remains large: Again, when N_2 increases, the neutrino becomes Majorana-like and decouples from the Higgs, thus exclusions can no longer be made.

B. Tevatron

The CDF experiment has recently completed an inclusive like-sign dilepton analysis using 6.1 fb^{-1} of data [24]. Though Tevatron's $gg \rightarrow h$ production cross section is smaller than LHC's, it is still possible to use the inclusive like-sign dilepton search to constrain fourth generation parameter space for Higgs masses under 200 GeV. First of all, in a fourth generation scenario, Higgs production from gluon fusion is substantially enhanced. In addition, in the regime of lighter Higgs masses, the lightest Majorana neutrinos occupy a significant or even dominant portion of the Higgs branching fraction, and we thus expect many like-sign dilepton events from Higgs production. In addition, Tevatron's inclusive like-sign dilepton search did not require the large invariant mass cut, increasing the sensitivity to the fourth generation Higgs decays where the neutrino is light.

We consider again the process $gg \rightarrow h \rightarrow N_1 N_1 \rightarrow W W \ell \ell \rightarrow \ell \ell + q q' + q q'$. CDF's search considered both electrons and muons in the final state. Note that the weakest bound in fourth generation lepton scenario occurs when the fourth generation neutrino decay, $N_1 \rightarrow W \ell$, is flavor democratic: then the lightest allowed neutrino mass is 61.2 GeV. We expect that we will be able to improve the bound using the inclusive like-sign dilepton search only in the flavor

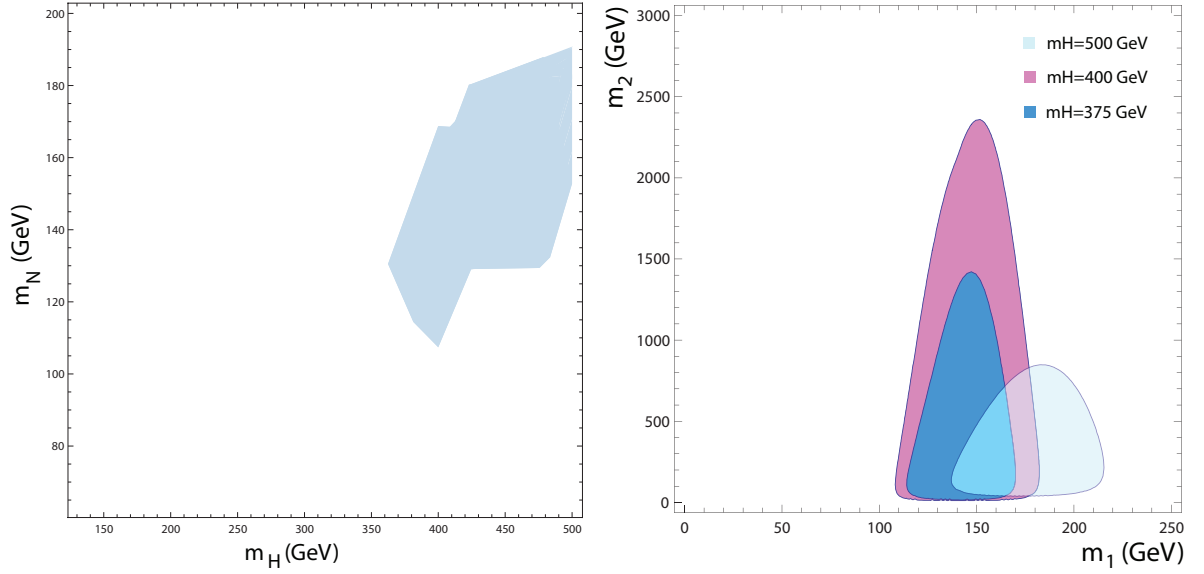


FIG. 5: Exclusions at 95 percent confidence level from the ATLAS inclusive like-sign dilepton search in (left) the N_1, m_h mass plane for the value $m_{N_2} = 300$ GeV, and (right) the N_1, N_2 mass plane for Higgs masses of 375, 400, and 500 GeV.

democratic neutrino decay scenario. To calculate the acceptance for CDF's cuts, we generated events in MADGRAPH and showered them with PYTHIA. We use CDF's inclusive like sign dilepton cuts:

- 2 same-sign leptons
- the most energetic lepton $p_T > 20$ GeV
- next most energetic lepton $p_T > 10$ GeV
- $|\eta_\ell| < 1.1$
- veto of like-sign electrons with invariant masses 86-96 GeV
- in tri-lepton events, veto of opposite-sign leptons with invariant masses 86-96 GeV

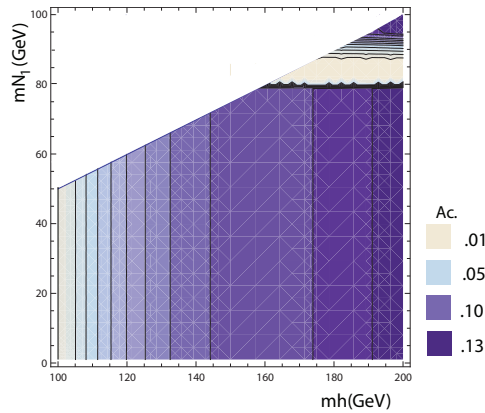


FIG. 6: Acceptance of CDF's like-signed dilepton selection in the m_h, N_1 mass-plane.

Applying the CDF selection to our simulated events, we find efficiencies ranging up to 13%, see Figure 6. We see that the efficiency increases as the Higgs mass increases, as the decay products of the Higgs become harder. In addition, we see a decrease in the efficiency for values of the N_1 mass above the W mass. This is expected as the lepton in the heavy neutrino decay $n_1 \rightarrow W\ell$ will be extremely soft for neutrino masses just above the W mass.

Backgrounds for this search are quite small and come from diboson production; WZ and ZZ , as well as from misidentified leptons due to jets in top quark pair production or W +jet events. Higgs branching fractions into neutrinos in this range may be quite large, as one can see from Figures 2 and 3. We may expect to be able to rule out the existence of very light neutrinos at 95 percent confidence level in the case that decays to leptons are flavor democratic. Figure 7 shows exclusions at 95 confidence level in the neutrino mass plane for 4 benchmark values of the Higgs mass. Note that for Higgs masses up to $2m_W$, we exclude N_1 masses below the W mass, unless we are into the very deep Majorana region. Once the Higgs mass gets larger, the branching fraction to neutrinos is much less, and we can no longer rule out substantial pieces of parameter space.

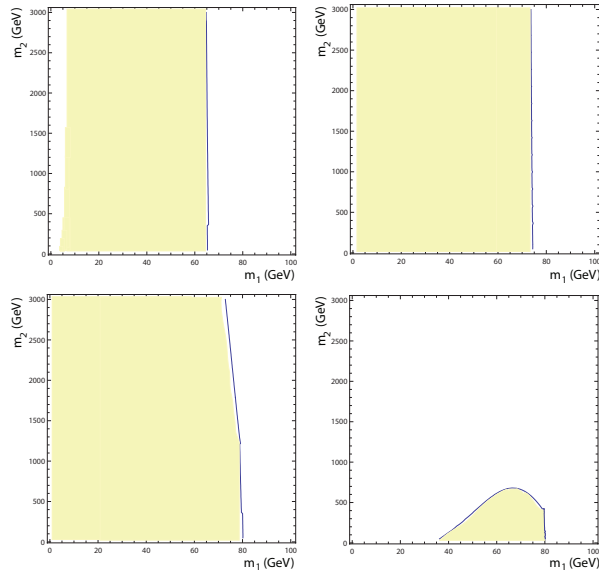


FIG. 7: Plots of exclusion at 95 percent confidence in the N_1 N_2 mass plane for Higgs masses (clockwise from top left) of 131, 150, 200, and 180 GeV by Tevatron's inclusive like-sign dilepton search.

V. CONCLUSIONS

We have shown that Higgs production and decay plays a significant role in probing the existence of fourth generation leptons. The existence of fourth generation quarks would yield a substantial increase in Higgs production from gluons fusion. In addition, the Higgs has large branching fractions into fourth generation neutrinos for Higgs masses up to about 500 GeV. If the fourth generation neutrinos have both Dirac and Majorana states, we find that there are many Higgs decays into the channel $h \rightarrow N_1 N_1 \rightarrow WW\ell\ell$ which yield many like-sign dilepton events.

We have calculated exclusion curves using CDF and ATLAS limit. If the heavy neutrinos decay exclusively to muons, the ATLAS inclusive like-sign muon analysis can exclude lightest neutrino masses between 100 and 200 GeV unless one is in the deep Majorana regime for fourth generation neutrinos. In addition CDF's inclusive like-sign dilepton analysis excludes the lightest allowed fourth generation neutrinos in the case that the neutrino decay is flavor democratic.

There are many prospects for fourth work along these lines. The LHC experiments will soon publish results with nearly 1 fb^{-1} of data. Further investigation into like sign dileptons may rule out even more fourth generation parameter space. However, if fourth generation neutrinos exist, there may be a surprising new channel in which to find the Higgs. In this case, if the Higgs mass is below 500 GeV, a few percent of the Higgs branching fraction will be to fourth generation neutrinos, and hence to like-sign dileptons with many jets. It may be possible to perform a search for the Higgs in this distinctive and low background region. A similar search, with hard like-sign dileptons and jets was proposed to look for a fourth generation charged lepton and neutrino pair ([25]), one would expect in a fourth generation scenario with Higgs production cross section around 10 picobarns, prospects would be quite good for Higgs discovery in this channel.

There is also a possibility for fourth generation scenarios which evade all current bounds and make for interesting Higgs physics; this is the case where the dominant branching fraction of fourth generation neutrinos is into taus. Here the bound on fourth generation neutrino mass is quite light, only 61.2 GeV. Here, for Higgs masses under 160 GeV it

is still possible that the dominant Higgs decay is to fourth generation neutrinos; this is a new hidden Higgs scenario. The dominant Higgs decay channel would then be $h \rightarrow N_1 N_1 \rightarrow WW\tau\tau$, beating the standard $h \rightarrow b\bar{b}$ signal by many orders of magnitude; this presents an interesting but difficult scenario for Higgs discovery.

Acknowledgments

This work was supported in part by DOE grant number DE-FG03-92ER40689.

-
- [1] P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **517**, 75 (2001) [arXiv:hep-ex/0107015].
 - [2] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 121801 (2007) [arXiv:0704.0760 [hep-ex]].
 - [3] L. M. Carpenter and A. Rajaraman, Phys. Rev. D **82**, 114019 (2010) [arXiv:1005.0628 [hep-ph]].
 - [4] G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, Phys. Rev. D **76**, 075016 (2007) [arXiv:0706.3718 [hep-ph]].
 - [5] Q. Li, M. Spira, J. Gao and C. S. Li, Phys. Rev. D **83**, 094018 (2011) [arXiv:1011.4484 [hep-ph]].
 - [6] T. Banks, L. M. Carpenter and J. F. Fortin, JHEP **0809**, 087 (2008) [arXiv:0804.2688 [hep-ph]].
 - [7] L. M. Carpenter, D. E. Kaplan and E. J. Rhee, arXiv:0804.1581 [hep-ph].
 - [8] S. Chang and N. Weiner, JHEP **0805**, 074 (2008) [arXiv:0710.4591 [hep-ph]].
 - [9] S. Chang, P. J. Fox and N. Weiner, JHEP **0608**, 068 (2006) [arXiv:hep-ph/0511250].
 - [10] B. Bellazzini, C. Csaki, J. Hubisz and J. Shao, Phys. Rev. D **83**, 095018 (2011) [arXiv:1012.1316 [hep-ph]].
 - [11] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010)
 - [12] P. Abreu *et al.* [DELPHI Collaboration], Phys. Lett. **B274**, 230-238 (1992).
 - [13] A. Lenz, H. Pas and D. Schalla, J. Phys. Conf. Ser. **259**, 012096 (2010) [arXiv:1010.3883 [hep-ph]].
 - [14] L. M. Carpenter, arXiv:1010.5502 [hep-ph].
 - [15] K. Belotsky, D. Fargion, M. Khlopov, R. Konoplich and K. Shibaev, Phys. Rev. D **68**, 054027 (2003) [arXiv:hep-ph/0210153].
 - [16] W. Y. Keung and P. Schwaller, JHEP **1106**, 054 (2011) [arXiv:1103.3765 [hep-ph]].
 - [17] A. Rajaraman and D. Whiteson, Phys. Rev. D **82**, 051702 (2010) [arXiv:1005.4407 [hep-ph]].
 - [18] A. Rajaraman and D. Whiteson, Phys. Rev. D **81**, 071301 (2010) [arXiv:1001.1229 [hep-ph]].
 - [19] Y. Katsuki, M. Marui, R. Najima, J. Saito and A. Sugamoto, Phys. Lett. B **354**, 363 (1995) [arXiv:hep-ph/9501236].
 - [20] G. Aad *et al.* [ATLAS Collaboration], arXiv:1108.0366 [hep-ex].
 - [21] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].
 - [22] P. Meade and M. Reece, arXiv:hep-ph/0703031.
 - [23] T. Sjostrand *et al.*, Comput. Phys. Commun. **238** 135 (2001).
 - [24] <http://www-cdf.fnal.gov/physics/exotic/r2a/20110407.samesign dileptons/lcdil.pdf>
 - [25] L. M. Carpenter, A. Rajaraman and D. Whiteson, arXiv:1010.1011 [hep-ph].